The Compact Muon Solenoid Experiment
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Commissioning and Early Measurements of the DT Muon Detector of CMS at the LHC

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(on behalf of the CMS Muon Barrel Collaboration)

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Abstract—The Drift Tubes (DT) constitute one of the components of the Barrel Muon Detector of the CMS experiment at the CERN's LHC proton-proton collider. In this paper, the final assembly, and the strategy and the results of the commissioning of the DT detector are presented, together with first measurements on cosmic rays, with and without the magnetic field. Although the DT are not best suited for halo muons surrounding the LHC beams, they were nonetheless able to record muons passing through the barrel of CMS during the few days of LHC beam operation in September 2008. The general experience gained by operating the DT's both as a tracking detector and as a trigger for the whole CMS experiment are also reviewed.

Index Terms—LHC, CMS, Muons, Drift Tubes, Hadron Collider, Commissioning, Tracking.

I. INTRODUCTION

THE Compact Muon Solenoid (CMS) is a general-purpose detector designed to run at the highest luminosity at the LHC [1]. A schematic view of the CMS detector is shown in Fig. 1, together with an indication of its barrel components. It is built around a high-field (as large as 4T) super-conducting solenoid. Such a high field was chosen in order to allow the construction of a compact tracking system on its interior, and still performing good muon tracking on the exterior. The magnetic flux is returned through 1.5 m of saturated iron yoke, instrumented with four interwoven muon stations. The barrel part of the yoke (namely, the one with pseudorapidity $|\eta| < 1.2$) is sectioned into five wheels (named YB-2, YB-1, YB0, YB+1 and YB+2) movable on rails with air pads. The central wheel supports the vacuum tank which contains the super-conducting coil. CMS is located in a cavern at the pit number 5 of the LHC. In order to make use of the time needed for completing the cavern civil engineering, the detector has been pre-assembled and tested in a hall on the surface, while final assembly and commissioning took place underground.

The muon system for a general purpose experiment at the LHC proton-proton collider must perform muon triggering, muon identification, and possibly improve the muon momentum measurement provided by the inner tracking detectors. Amongst the requirements for such a muon system there is the possibility of triggering on single and multiple muons with p_T thresholds as low as about 10 GeV/ c , and unambiguous assignment of the exact beam crossing to which that trigger refers to. Muon chambers external to the calorimeters may

Fig. 1. The CMS detector.

improve the measurement of track parameters for very energetic muons, less affected by multiple scattering than lowest momentum ones, with the aim of having a correct charge assignment up to $p_T(\mu)$ as large as several TeV/ c .

To fulfill those physical requirements, three types of gaseous muon detectors [2] exist in CMS. Different detector technologies were chosen for the barrel and for the two endcaps. In the barrel, where the magnitude of the residual magnetic field is of the order of 2 Tesla in the iron return yoke and the neutron background and muon rate are expected to be as low as a few Hz/cm², Drift Tubes (DT) are used. In the endcaps, where larger magnetic fields and higher particle rates will be met, Cathode Strip Chambers (CSC) are best suited. Moreover, Resistive Plate Chambers (RPC) allow for the trigger redundancy both in the barrel and in the endcaps.

The first selection of muons is performed on-line by the Level-1 Trigger (L1) [3], which preselects the most interesting collisions for further evaluation and possible permanent storage by the High-Level Trigger (HLT) [4]. L1 is a custom-designed, largely programmable electronic system, whereas the HLT is a farm of industrial processors.

Centrally produced muons are detected in the silicon tracker, in the calorimeters, and then identified and measured by the DT's in four concentric Muon Barrel stations. Those stations are arranged inside the five wheels in which the barrel yoke is segmented. In the wheels, four parallel DT stations cover everyone of the twelve 30 degrees sectors on which the yoke is divided. Special care has been taken to avoid pointing cracks

Fig. 2. Drawing of a DT cell.

and to maximize the geometric acceptance: the chambers are staggered from station to station so that a high- p_T muon near a sector boundary crosses at least three stations. The basic element of the DT detector is the aluminium drift cell, which is shown in Fig. 2 together with a schematization of the electric field within it: it has a cross section of $42 \times 13 \text{ mm}^2$ and a variable length of the order of 2.5 m. Cells are filled with an $\text{Ar}(85\%)\text{-CO}_2(15\%)$ gas mixture, and have at their center a stretched anode wire. When a muon or any charged particle passes through the volume it knocks electrons off the atoms of the gas. These follow the electric field ending up at the positively-charged wire. Adjacent DT cells are arranged in layers, each with up to 60 tubes. Four layers form the so-called superlayer (SL). Each muon station contains two superlayers oriented along the z -axis and designed to give a muon vector in the r - ϕ plane, with better than $100 \mu\text{m}$ precision in position and better than 1 mrad in direction. The first three stations also contain one superlayer of four planes of orthogonal drift tubes measuring the z coordinate.

Given such a segmentation, 250 DT chambers exist overall in CMS, yielding a total number of 180k channels. DT chambers were produced at four production sites in Italy (Legnaro and Torino), Spain (CIEMAT) and Germany (Aachen), by a large international collaboration which includes also Bologna and Padova. To allow for the completion of the civil engineering infrastructure in the underground hall housing nowadays the CMS detector, insertion inside the iron return yoke of the CMS magnet of the DT's and of the minicrates, containing their trigger and readout electronics, began on the surface, letting aside only those sectors where the cranes for descending them in the pit would have been attached. DT installation was completed underground, with the last module finally inserted in October 2007. Fig. 3 shows one of the wheels fully equipped with all its DT stations in its final position down into the CMS cavern.

DT muon chambers and their readout and trigger electronics were individually extensively tested before and after installation. Calibration, alignment and commissioning tools, before the availability of the LHC beam collisions, include cosmic rays, lasers, test pulses and patterns, as well as test beams. Measurements included the identification of local patterns generated by cosmic muons and calibration test pulses, as well as the measurement of the drift velocity and of the starting time of the muon pulses, for synchronization purposes. It is worth

Fig. 3. One of the CMS barrel wheels with all its DT stations installed, down into the LHC pit 5.

noting that only 0.2% of all the DT channels was found dead after the final detector installation and commissioning.

II. DT LOCAL COMMISSIONING

After having inserted all chambers in their final position inside the CMS yoke and cabled for powering and data transferring, to become a fully operational detector the DT have to overcome several test challenges. First of all, all chambers and minicrates were individually tested for correct functioning and cabling. This task was started already when the stations were mounted on the surface hall, by using cosmic muons and test pulses. Whenever needed, interventions were planned and operated in order to make all parts of the detector ready for the operations. This chamber commissioning was completed afterwards in the cavern, with some amount of extra challenge whenever a repair was needed because of the little space at disposal downstairs for the interventions.

As soon as the integration progressed, from such a chamber commissioning one moved to the sector commissioning, where four stations at a whole could be operated and read-out together, thus allowing also the tracking of cosmic muons between different chambers, as it is shown in Fig. 4 where a cosmic muon is clearly seen crossing all four DT stations in sector 2.

The subsequent step of the detector commissioning was the so-called wheel commissioning, where all (or most of the) sectors in a whole wheel were tested and commissioned together. For every single DT chamber, a complete mapping of the DT cell and trigger efficiencies was performed. Typical cell efficiency to cosmic rays range between 90% and 100%, with an overall rate of dead cells as low as 0.2% of the total. The position of the dead cells, whenever found, is included in the detector DataBase, to allow for an optimized description and realistic simulation of its performance.

A. Drift time and t_0 measurements

Amongst the measurements done already during the local commissioning and relevant for the final DT calibration are the

Fig. 6. Measurement of the cosmic muons charge ratio in the DT's during the Magnet Test and Cosmic Challenge of 2006. CMS results (black dots) are shown with their statistical (thick bars) and systematical (thin bars) errors, and they are compared with previous measurements of the same ratio.

the preceding experiments [11]. Even with only a few sectors switched on, the precision of the CMS results is already almost comparable with the one of the previous experiments. Further improvements of this measurement in CMS are expected after having analyzed the large amount of data collected with all sectors and wheels in the underground cosmic challenges with the magnetic field on, as performed underground in the second half of 2008.

IV. DT ALIGNMENT

The geometry of the DT chambers was carefully monitored and inspected with optical survey measurements during their assembly and after their final installation in CMS. The relative position of the chambers inside the wheel was first determined with photogrammetry of the elements and of the whole detector, with null magnetic field: this represented an excellent starting point for the survey of the detector alignment, reaching a precision of about 1 mm. An analog/digital optical system which uses laser pulses and a dedicated instrumentation [12] links barrel and endcap muon detectors and reduces the uncertainty on the overall geometry down to $\sim 250 \mu\text{m}$. Further refinement of the alignment precision can be obtained offline by analyzing large samples of clean tracks. For the barrel muon detectors, unambiguous samples of prompt muons during the LHC collisions will be extracted from $Z^0 \rightarrow \mu^+\mu^-$ decays. Cosmic muons will also be useful for the detector alignment during the experiment lifetime, and in particular they are the only sample available before the onset of the LHC collisions.

In spite of a careful design, installation and survey, a few effects can cause a misalignment of the muon detector components. First of all, a gravitational displacement has been observed, which results in a shift as large as 0.8 mm in the most affected positions inside the wheel. Furthermore,

Fig. 7. Results of the extrapolation in the r - ϕ plane of the muon track position between two consecutive chambers in wheel 0, sector 3, before alignment corrections are applied: the in-out and out-in extrapolations are compared.

additional distortions of similar size can show up when the magnet is switched on.

To monitor offline the alignment of the detector components, four levels of alignment are foreseen for the DT's:

- Internal geometry of all chambers;
- Alignment of chambers within the wheel;
- Wheel-to-wheel alignment;
- Alignment of the DT with respect to the inner tracker.

The general method used in the offline alignment is to extrapolate the track segments between consecutive chambers and/or wheels, and modify the relative geometry until those extrapolations coincide. An example of the alignment survey in the r - ϕ plane between two chambers in the same sector and wheel before applying the correction to the DT geometry is shown in Fig. 7. Up to now, the internal alignment of all chambers and the alignment within the same wheel have been already performed with cosmics, and their outcomes have been propagated to the detector description data-base. Wheel-to-wheel and alignment with the inner tracker are still in progress.

V. DT'S IN GLOBAL DATA TAKING

With the completion of the installation of the detector in the experimental cavern, several periods of global data taking of cosmic muons with all available CMS components were performed during 2008, and others will follow until the startup of the LHC collisions. They were mainly aimed at detector integration, DAQ and trigger deployment, synchronization and alignment, test and refinement of the global reconstruction. Those global data taking were done both with and without the magnetic field. In particular, four continuous weeks of operation with the magnet on ended on November 11 2008. 296 M cosmics were collected with, amongst the others, the Silicon Strip tracker and the DT's included in the run.

While other CMS subdetectors were added as soon as they were ready, the DT were there since the very beginning of those exercises, as they always provided the trigger for the global DAQ. In the latest tests all CMS tracker components and calorimeters were available, and the cosmic muons could finally be traced through the muon system (DT, CSC and RPC), the tracker (TOB and TIB), the ECAL and the HCAL. A global track fit could be provided, resulting in a large amount of excellent data being used also for global alignment.

To certify the passage of the cosmic muon through all inner CMS barrel component a "di-muon" trigger was provided by

Fig. 8. A cosmic muon passing all barrel CMS subdetectors in the cosmic challenge for the global commissioning of CMS.

the DT in which the coincidence of two segments in the top and bottom sectors were required, each with segments reconstructed in at least two stations. To improve the trigger efficiency, a delay between the top and the bottom sectors of the DT was also included, in order to take into account the time of flight of the muons between the two positions.

A nice example of a cosmic muon tracked in the DT and in the inner tracker, and releasing signals in the electromagnetic and hadronic calorimeters of CMS is shown in Fig. 8

A. Commissioning and measurements with cosmic muons

The quality of the reconstruction and determination of tracking parameters of cosmic muons in the DT is demonstrated by the image obtained by extrapolating the muon tracks reconstructed from the cosmic data collected in may/june 2008. Fig. 9 shows the number of muons reconstructed as function of the extrapolation of the position on the surface above the CMS cavern. One can notice an accumulation of events in a roughly circular surface located above and slightly displaced from the CMS experimental apparatus. This can be easily recognized as being the image of the shaft used to lower the big components of CMS during its construction.

A further characterization of the muons coming from the shaft can be derived from Fig. 10, where the fraction of muons which have segments reconstructed both in the upper and in the lower part of the detector is plotted as function of the same coordinates at the ground surface. Having no magnetic field in the data used to obtain those figures, a determination of the muon momentum is impossible. However, it is reasonable to assume a larger momentum for muons which cross all the apparatus from top to bottom with respect to those muons which get stopped somewhere in the detector material included between the upper and lower part of the DT ring. Using such an estimate, the figure demonstrates how muons not coming from the shaft are relatively much more energetic than those coming from it, as it must be expected since muons able to penetrate ~ 100 m thick ground have necessarily to be very energetic.

Fig. 9. Extrapolation of the muon track to the earth surface above the CMS detector. The position of the detector is approximated, and serves as to guide the eyes in recognizing the origin of the accumulation of muon events as the shaft above the CMS detector, slightly displaced on one of its sides.

Fig. 10. Fraction of muons with segments reconstructed both in the upper and in the lower part of the DT detector, as function of the extrapolation of the muon track to the earth surface above the CMS detector.

B. Commissioning and measurements with circulating LHC beams

On September 10, 2008, at 12:30 the LHC team at CERN finally succeeded in circulating the first proton beams in the machine. The beams were circulated at the injection energy of 450 GeV, first in one direction and then in the other direction. Since there were no collisions, no events originating in the interaction point could be registered. Proton beams are however accompanied by a halo of muons traveling in the same direction of the beams and slightly displaced with respect to

Fig. 11. Graphical representation of the hit recorded in the CMS subdetector during a dump of the LHC beam some 150 m upstream of CMS. Top left is the HCAL and Hadron Forward; top right is the ECAL. Below are the projections perpendicular to the beam axis: on the left DT and ECAL, and on the right DT and HCAL. Inner tracker was off during the event.

them. Forward detectors of CMS were perfectly positioned to record those halo muons, and those events are actually very conveniently used to calibrate and align the forward muon detectors of CMS.

Being in the barrel part of CMS, and with the detector planes parallel to the LHC beams, the DT are certainly not well suited to record halo muons. Indeed, DT (and the whole CMS) could record gigantic events when the beam 1 of LHC was dumped onto a collimator some 150 m upstream of CMS. In such events, it has been estimated that $\sim 2 \times 10^9$ protons hit the collimator. Between 100 and 1000 TeV of energy was observed in the ECAL and HCAL, and between 10^5 and 10^6 muons were recorded in CMS. With all the detector illuminated it could have obviously resulted hard reconstructing any muon track. However, as can be seen in Fig. 11, which shows the hits recorded in the various subdetectors of CMS during that gigantic event, the DT got almost fully illuminated in the three innermost rings of stations, with several hits recorded even in the fourth ring, at more than 7 m distance from the beam axis.

Unfortunately, after a successful start, on September 19 the LHC suffered an incident, with sudden leak of helium into the cavern and damage of several dipole and quadrupole magnets [13]. This incident forced withdrawing from the ongoing accelerator commissioning with beams and cancelling the rest of the program for 2008. CMS and the other experimental collaborations at the LHC had to postpone to the coming year all foreseen data taking with colliding proton beams.

VI. CONCLUSIONS

In this paper, the final installation and the commissioning of the DT muon detector of CMS were summarized. Dedicated local data taking and global data taking, together with the other subdetectors of CMS, were able to prepare the DT for the task and challenges expected in the forthcoming LHC runs. Calibrations and final alignment of the various components of the detector were performed, and are at present being refined.

A few physics measurements have been already done on cosmic rays. In particular, the measurement of the cosmic charge ratio represented a first exercise on real data of a complete physics measurement, with the inclusion of all systematics and the production of a result to be compared with others in the literature. The “muonography” of the earth surface some 100 m above the detector demonstrated the high level of accuracy reached by the tracking in CMS, and in the muon system in particular.

The DT are routinely and solidly used to provide the trigger to the whole CMS in the global acquisition runs. They were also able to record some signal coming from the first circulating beams of LHC in September 2008, although not being certainly in the best position to accept particles traveling parallel to the LHC beam, as it is the case when there are no collisions.

The whole DT muon barrel community is eagerly waiting for the first LHC collisions. Anyhow, already during the commissioning the DT have certainly demonstrated being ready for the exciting periods ahead.

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